Raw Materials Supply

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Abstract The pressure on reducing environmental footprint is facilitating the emergence of energy supply chains that have biomass as main feedstock. For the development of efficient energy supply chains from biomass it is required to properly integrate the various elements that comprise such systems (e.g., biomass supply, pre-treatment facilities and technologies for biomass to energy and/or fuels conversion). Additionally, it is recognised that a concerted effort is required, embracing the different supply chain entities, in order to correctly estimate environmental burdens and to propose effective environmental strategies. This chapter proposes the use of a mathematical modelling approach as an analytical tool that can support decision-making towards accomplishing the design and planning of efficient multiple source—multiple product bio-energy supply chains. The mathematical formulation of this problem becomes a multi-objective MILP (moMILP). Criteria selected for the objective function are the net present value (NPV) and the overall environmental impact, which is computed using the Impact 2002+ indicator. The main advantages of this approach are highlighted through a case study of a biomass-based supply chain that comprises different components geographically distributed over Spain. For comparison purposes, such a supply chain is contrasted to one embracing coal usage.

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Notation

Indices

e	Suppliers
f, f'	Facility locations
i	Tasks
j	Equipment technology
s	Materials (states)
t, t'	Planning periods
a	Mid-point environmental impact categories
g	End-point environmental impact categories

Sets

A_g	Set of mid-point environmental interventions that are combined into end-point damage factors g
E_{rm}	Set of suppliers e that provide raw materials
$\hat{E}_{\mathrm{prod}}$	Set of suppliers e that provide production services
$\bar{E}_{\mathrm{tr}}$	Set of suppliers e that provide transportation services
F_e	Set of locations f where supplier e is placed
FP	Set of materials s that are final products
I_j	Set of tasks i that can be performed in technology j
$\bar{J}_e$	Technology j that is available at supplier e
$\tilde{J}_f$	Technology j that can be installed at location f
J_i	Technologies that can perform task i
Mkt	Set of market locations
NTr	Set of non-distribution tasks
RM	Set of materials s that are raw materials
Sup	Set of supplier locations
T_s	Set of tasks producing material s
$\bar{T}_s$	Set of tasks consuming material s
Tr	Set of distribution tasks

Parameters

A_{sft}	Maximum availability of raw material s in period t in location f
Dem_{sft}	Demand of product s at market f in period t
$\mathrm{distance}_{ff'}$	Distance from location f to location f'
FCFJ_{jft}	Fixed cost per unit of technology j capacity at location f in period t
I^J_{ft}	Investment required to establish a processing facility in location f in period t
$\mathrm{Norm}F_g$	Normalising factor of damage category g
Price_{sft}	Price of product s at market f in period t
Price^J_{jft}	Investment required per unit of technology j capacity increased at facility f in period t

rate	Discount rate
Water_s	Moisture for material s
$\text{Water}_{ij}^{\max}$	Maximum moisture for task i performed in equipment j
α_{sij}	Mass fraction of task i for production of material s in equipment j
$\bar{\alpha}_{sij}$	Mass fraction of task i for consumption of material s in equipment j
β_{jf}	Minimum utilisation rate of technology j capacity that is allowed at location f
ζ_{ag}	g end-point damage characterisation factor for environmental intervention a
$\theta_{ijff'}$	Capacity utilisation rate of technology j by task i whose origin is location f and destination location f'
$\rho_{eff't}^{\text{tr}}$	Unitary transportation costs from location f to location f' during period t
$\tau_{ijfet}^{\text{ut1}}$	Unitary cost associated with task i performed in equipment j from location f and payable to external supplier e during period t
τ_{sfet}^{ut2}	Unitary cost associated with handling the inventory of material s in location f and payable to external supplier e during period t
χ_{est}	Unitary cost of raw material s offered by external supplier e in period t
$\psi_{ijff'a}$	a environmental category impact CF for task i performed using technology j receiving materials from node f and delivering it at node f'
ψ_{ija}^{T}	a environmental category impact CF for the transportation of a mass unit of material over a length unit

Binary Variables

V_{jft}	1 if technology j is installed at location f in period t, 0 otherwise

Continuous Variables

DamC_{gft}	Normalised end-point damage g for location f in period t
$\text{DamC}_{g}^{\text{SC}}$	Normalised end-point damage g along the whole SC
EPurch_{et}	Economic value of purchases executed in period t to supplier e
ESales_t	Economic value of sales executed in period t
FAsset_t	Investment on fixed assets in period t
FCost_t	Fixed cost in period t
F_{jft}	Total capacity of technology j during period t at location f
FE_{jft}	Capacity increment of technology j at location f during period t
IC_{aft}	Mid-point a environmental impact associated to site f which rises from activities in period t
Impact_{f}^{2002}	Total environmental impact for site f
$\text{Impact}_{\text{overall}}^{2002}$	Total environmental impact for the whole SC
LHV_{si}	Lower heating value for material s in task i
NPV	Net present value
$P_{ijff't}$	Activity magnitude of task i in equipment j in period t whose origin is location f and destination location f'

$Pv_{sijff't}$	Amount of material *s* for flexible task *i* in equipment *j* in period *t* whose origin is location *f* and destination location *f′*
Profit_t	Profit achieved in period *t*
$\mathrm{Purch}_{et}^{\mathrm{pr}}$	Amount of money payable to supplier *e* in period *t* associated with production activities
$\mathrm{Purch}_{et}^{\mathrm{rm}}$	Amount of money payable to supplier *e* in period *t* associated with consumption of raw materials
$\mathrm{Purch}_{et}^{\mathrm{tr}}$	Amount of money payable to supplier *e* in period *t* associated with consumption of transport services
$\mathrm{Sales}_{sff't}$	Amount of product *s* sold from location *f* in market *f′* in period *t*
S_{sft}	Amount of stock of material *s* at location *f* in period *t*

Superscripts

L	Lower bound
U	Upper bound

Acronyms

B-NET	Biomass utilisation networks
BM	Biomass
CBA	Cost benefit analysis
CCS	Carbon capture and storage
CF	Characterisation factors
DFCF	Discounted-free-cash-flow
Eco-indicator 99	Damage environmental metric
EISA	Energy Independence and Security Act
FWR	Forest wood residues
GHG	Greenhouse gas
GrSCM	Green supply chain management
IMPACT 2002+	Mid-point and end-point (damage) environmental metric
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
LCI	Life cycle inventory
STN	State task network
moMILP	Multi-objective mixed integer linear programming
NPV	Net present Value
SCM	Supply chain management
STN	State task network

1 Introduction

Global trends are promoting the utilisation of renewable sources of energy. For instance, the European Union has established a target of 20% share of renewable energy out of the total European energy consumption by 2020 [1]. Biomass energy generation is an option that is expected to play an important role in the renewable energy mix. As a matter of fact, the USA in its Energy Independence and Security Act (EISA) of 2007 states that advanced biofuels shall supply at least 21 billion gallons of US motor fuels by 2022. It is recognised that in order to achieve these targets efficient networks to supply sustainable amounts of biomass required, cost-effective technologies to convert biomass and improved distribution infrastructures to deliver the final product (i.e., energy or fuel) are to be developed [2]. Even more, the efficient integration of these three elements is equally relevant to reach the posed goals. In this chapter, we propose a supply chain modelling approach as a tool that can support decision-making towards accomplishing such integration.

The concept of supply chain (SC) refers to the network of interdependent entities (i.e., processing sites, distributors, transporters, warehouses and raw material suppliers) which is the processing and distribution channels of a product from origin of its raw materials to final delivery to the customer. Then, supply chain management (SCM) can be defined as the management of material, information and financial flows through a SC that aims at producing and delivering goods or services to consumers [3]. Note that a SC is comprised by components that may be geographically distributed. One of the main objectives of SCM is to synchronise and coordinate the flows of materials that go through the different processes so that the final product is delivered in a most efficient manner. This is especially important for biomass to energy projects which are highly geographically dependent and whose profitability can be strongly influenced by the location of the different processes and biomass sources. Commonly, biomass production and transportation account for a significant part of the whole bioenergy supply chain cost [4]. Therefore, a tool capable of evaluating the possible trade-offs between the different feedstock sources, each one with specific properties (i.e., moisture and energy density) and the location of processing sites and consumption is a requisite to develop efficient bioenergy networks.

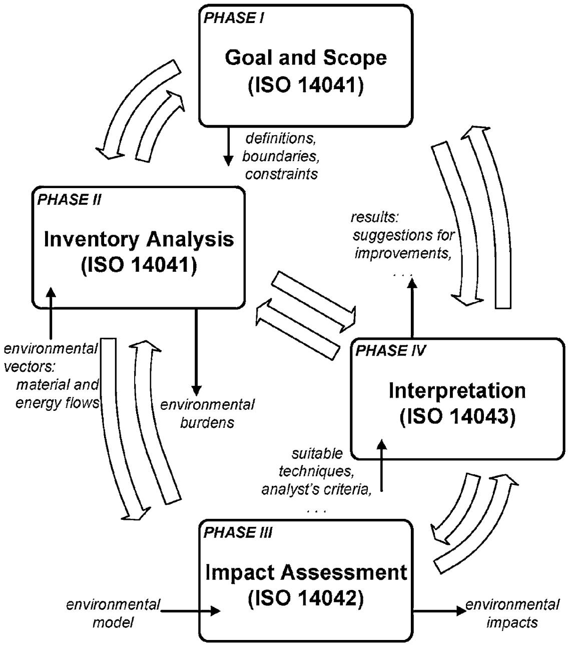
The interest on SC biomass-based for different final purposes, ranging from energy or fuels production, has increased since the 90s, thus being a relatively new concept and also a consequence of the current energy paradigm. Typically, a biomass SC problem considers the possible use of multiple sources of biomass. It is also important to point out that biomass usually requires some pre-treatment before its use. This previous treatment is done aiming at obtaining a homogenised or densified biomass, whether in terms of mass or energy. In this sense, Hamelinck et al. [5] considers an international bioenergy SC taking into account the fact that biomass production and consumption do not need to be in the same region, i.e., that biomass residues and energy crops are in excess in some areas, but scarce in others, and energy import regions (Western Europe) do not match with the higher biomass production areas (Scandinavia, Eastern Europe and Latin America). Biomass compacted into briquettes or pellets can be used to save transport use because of their smaller volume. Nevertheless, there exists a trade-off between the type of transport, the distance and the densification methods since the cost of biomass pre-treatments as a whole should not be higher than the compensated logistic costs. This is an important consideration to take into account when long distances should be covered. They demonstrate that an international bioenergy trade has real potential; however, governments must stimulate the biomass market in terms of prices, policies and social acceptance. Panichelli and Gnansounou [4] contemplate forest wood residues (FWR) from final cuttings to produce torrified wood that supplies a gasification unit in order to produce electricity. They are able to allocate biomass quantities between predefined combinations of candidate sites to find the best set of locations for the energy units. They state fix values for the torrefaction and gasification units, and take into account cost minimisation. A mixed integer linear program (MILP) that determines the optimal sizes and locations of biomass-based methanol plants (biofuel plants) is developed by Leduc et al. [6]. The objective function considered to be optimised is the operating costs plus the investment required to establish the biomass SC. The supply is given by poplar coppice, as energy crop, and the demand is based on gasoline-methanol car blend use. The possible consumer sites are the already existing gas stations in Austria, while methanol production is considered through the use of gasification plants. The evaluation of three scenarios is performed, based on different methanol-gasoline blends. By-production of heat is also considered as economic revenue, and CO_2 emissions are accounted finally, but not introduced in their model as an environmental objective to be accomplished. Later on, Ayoub et al. [7] present a methodology for designing and evaluating the biomass utilisation networks (so called B-NETs), which are process networks aiming at producing different bioproducts, from one or more biomass resources. The idea of this methodology is to provide a framework to create the underlying superstructure that relates the biomass resources to their products via current and possible future available processes; which can be used to develop an optimisation model. Their methodology is applied at a local level and proposes better biomass uses by means of economic parameters (costs) and environmental impacts accounting. The environmental indicator that the authors use accounts for emissions to air, water pollutants and solid wastes. The work of Rentizelas et al. [8] emphasises the multi-biomass seasonal availability and combines this fact with the biomass storage problem. The stages considered before the conversion plant of the raw material include harvesting and collection, in field handling and transport, storage, loading and unloading, transport and biomass pre-treatment. This last stage can be included in any of the abovementioned stages, and optimally could precede the transportation stage. Storage can be also located in the biomass origin in an intermediate step or at the power station site. The authors state that one of the main drawbacks of the use of biomass as a source is its relatively low density and heating value when compared, for instance, with other fossil sources. On a later work, Rentizelas et al.

[9] exemplify the fact that a biomass SC can account for multiple sources, as well as for multiple final products production, such as electricity, heat and cooling. They apply the methodology in a specific region of Greece. The results provide with optimal locations and investment details for potential investors. More recently, Van Dyken et al. [10] developed a linear optimisation model for planning the capacity expansions in energy systems where several alternative biomass and technologies are considered simultaneously. The main objective of this work is to present a generic model including different components such as sources, handling, processing, storage and final usage. Heating value, moisture content and bulk density are the key parameter changes that biomass undergo along the SC. The objectives to be optimised are the operating cost and emissions of the whole SC.

Definitely, energy policies are driven by environmental considerations, more specifically by the pressure on reducing greenhouse gas (GHG) emissions. In that sense, biomass is an energy source that is expected to provide significant reductions of environmental impacts related to GHG emissions when compared to the classical fossil fuels technologies. Therefore, it is relevant the integration of environmental thinking into SCM in order to assess such expected reduced environmental impacts. The aforementioned integration may be achieved through the emerging concept regarded as 'green supply chain management' (GrSCM). This concept considers the environmental interventions associated with the raw materials sourcing and selection, manufacturing process selection, delivery of final product to the consumers as well as end of life management of the product after its useful life [11]. Traditionally, the methodologies devised to assist SC operation and design have focused on finding a solution that maximises a given economic performance indicator while satisfying a set of operational constraints imposed by the manufacturing/processing technology and the topology of the network. In recent years, however, there has been a growing awareness of the importance of including environmental aspects as objectives and not constraints associated with the SC decision support [12, 13].

The environmental science and engineering community have developed several systematic methodologies for the detailed characterisation of the environmental impacts of chemicals, products and processes. All of these methodologies have embodied the concepts of life cycle, i.e., they are based on a life cycle assessment (LCA) which is described in a series of ISO documents [14]. The LCA framework includes the entire life cycle of the product, process or activity, encompassing extraction and processing of raw materials; manufacturing, transport and distribution; re-use, maintenance recycling and final disposal. Most importantly, it takes a holistic approach, bringing the environmental impacts into one consistent framework, wherever and whenever these impacts have occurred or will occur [15]. These methodologies are based on the incorporation of an optimisation step into the four classical phases that comprise an LCA study namely, goal definition, life cycle inventory—LCI, life cycle impact assessment—LCIA and interpretation (see Fig. 1). The idea of them is to determine process conditions or topology using a multi-criteria optimisation strategy in order to evaluate the trade-off between economic and environmental issues.

Fig. 1 Life cycle assessment steps [13]



As aforementioned, the concept of SC refers to the network of interdependent entities that constitute the processing and distribution channels of a product from the supply of its raw materials to its delivery to the final consumer. Because an LCA study ideally covers a cradle-to-grave approach, it can be clearly seen that LCA fits as a suitable tool for quantitatively assessing the environmental burdens associated with designing and operating a SC.

This chapter describes an analytical approach for the design and planning of a multiple source—multiple product interregional bioenergy SC taking into consideration not only economic issues but also environmental impact. The model accounts for different *biomass wastes* sources as well. The approach applies mixed integer modelling techniques. The model is optimised so as to select the most appropriate *pre-treatment* technologies, the most appropriate feedstock supplier for each process and the most convenient production and distribution profiles, in order to supply *electricity* and *hydrogen* to the customers. The mathematical model encompasses direct emissions, raw materials production and transport distribution emissions. LCA concepts are embedded in the approach, and going further in order to attain a comprehensive LCA application, not merely an overall environmental impact indicator is calculated but also partial environmental impact categories are studied. Furthermore, the impact associated with every SC echelon is mapped aiming at discovering possible opportunities to focus resources for environmental impact reduction.

2 Biomass Supply and Operations Planning

This chapter deals with the *strategic-tactical problem* associated to the optimal design and operation of a biomass SC network taking into account economical and environmental considerations. Generally speaking, the SC strategic level determines the network through which production and distribution serves the marketplace. The intent of the SC network design problem is typically to determine the optimal sourcing, manufacturing and distribution network for the new and existing product lines of a company (e.g., expansion or contraction of the business, introduction of new products, new strategic suppliers). The most common approach is to formulate a large-scale mixed integer linear program (MILP) that captures the relevant fixed and variable operating costs for each facility and each major product [16].

The considered biomass SC network consists of a number of potential locations where either a processing site or distribution centre or both of them can be installed, and suppliers at fixed locations which have available biomass with different characteristics. In general, each final product (energy or H_2) can be produced at several plants located at different locations using the different biomass wastes. The characteristics of the biomass can be changed by using the pre-treatment units (e.g., drying or torrefaction) so that the treated biomass meets the characteristics required to be used in further steps. Even more, such pre-treatments increase the energy content and bulk density of the biomass. By doing so the mass is reduced, thus significant savings in transportation may be achieved. The production capacity of each processing site is modelled by relating the nominal production rate per activity to the availability of the equipment technology at each plant. Distribution centres are described by upper and lower bounds on their material handling capacity and they can be supplied from more than one manufacturing plants. Given the way the problem is modelled, materials flow between any facilities may appear if selecting such flow allows improving the performance of the SC. A market demand may be served by more than one site.

The mathematical model is an analytical tool intended to support managers on planning decisions such as:

- The active SC nodes and links among them
- The facilities capacity expansion in each time period
- The product portfolio per plant, production amounts, utilisation level and transportation links to establish in the network alongside with material flows
- The amount of final products (energy or H_2) to be sold
- The environmental impact associated to each SC node or activity

A general schematic of the biomass energy SC is shown in Fig. 2. One can notice that it is comprised by four blocks: (i) sourcing, (ii) pre-treatment, (iii) generation and (iv) distribution. The sourcing block consists in collecting the different biomass that may be available from different regions and suppliers. Each type of biomass (e.g., pine waste, forest wood residues, olive pomace) has its

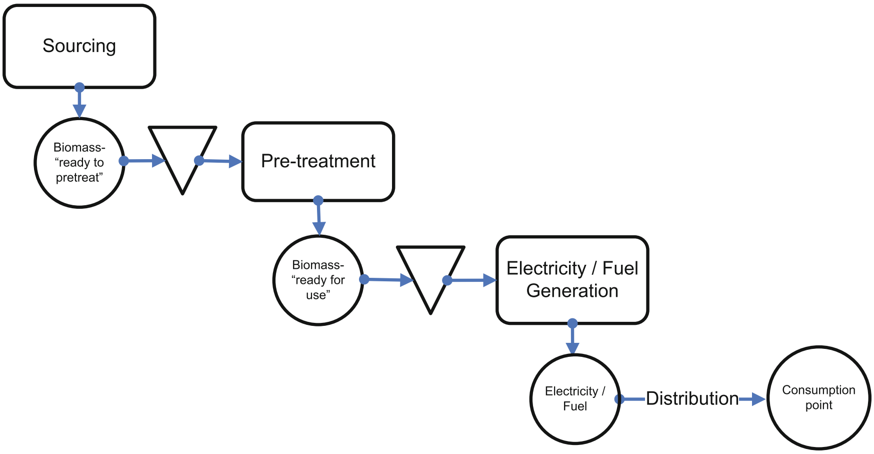


Fig. 2 General schematic of a biomass SC

own characterizing properties such as moisture content and heating value that determines its energy conversion efficiency. The pre-treatment block considers those activities that modify the quality (primarily moisture content) and/or shape of the biomass. Examples of this kind of processes are the chipping, pelletizing, drying, and torrefaction. Notice that these activities may be necessary, provided that there are some technologies which require feeding material to have a fixed maximum moisture content and/or some shape requirements in order to be processed. The generation block converts biomass into energy or any biofuel. Finally, the distribution block comprises those activities aiming at delivering the final product to the consumption points.

2.1 Supply Chain Drivers

All the aforementioned decisions will be taken such that an economic indicator, i.e., net present value (NPV), and an environmental impact metric, are optimised at the end of a predefined planning horizon.

2.1.1 Cost Benefit Analysis

The usage of NPV is the back bone of cost benefit analysis (CBA) of any project. A generic CBA consists of three steps: (i) valuation of the yearly costs and benefits of the project, (ii) discounting costs and benefits in future years to make them commensurate with present costs and benefits and (iii) calculation of the metric, (see Sect. 2.1 in chapter Global Clean Gas Process Synthesis and Optimisation).

Here, in order to compute the NPV, operational costs include those associated with production, handling of material, transportation and raw materials. Transportation costs are assumed to be linear functions of the actual flow of the product from the source echelon to the destination echelon. Revenue is obtained by the selling of products. Investments on facilities and equipment are also taken into account. The cash flows are discounted at a given return rate.

2.1.2 Environmental Metrics

Regarding the selection of environmental metrics, different methodologies have been developed; however, all of them rely on the accurate estimation of environmental interventions. Environment is compromised by industry mainly in two ways, namely, its emissions and the consumption of raw materials. See Sect. 2.3 in chapter Global Clean Gas Process Synthesis and Optimisation for further details.

Here, the environmental metrics used are the ones devised in the work of Humbert et al. [17], which presents an implementation working at both mid-point and end-point (damage) levels. For each environmental intervention two characterisation factors are proposed, which eases model implementation. Their methodology, IMPACT 2002+, is mainly a combination between IMPACT 2002 [18], Eco-indicator 99 [19] using egalitarian factors, CML [15], and the Intergovernmental Panel on Climate Change (IPCC) considerations for CO_2 emissions. IMPACT 2002+ has grouped similar category end-points into a structured set of damage categories by combining two main schools of impact model methods: classical impact assessment methods (CML/IPCC) and damage-oriented methods (Eco-indicator 99). This methodology proposes a feasible implementation of a combined mid-point/damage-oriented approach. It links all types of LCI results via 15 mid-point impacts (human toxicity, respiratory effects, ionizing radiation, ozone layer depletion, photochemical oxidation, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification/nitrification, aquatic acidification, aquatic eutrophication, land occupation, global warming, non-renewable energy and mineral extraction) to four areas of protection end-point categories (human health, ecosystem quality, climate change and global warming potential and resources).

This approach contains the advantages of being able to calculate both mid- and end-point indicators. Within the presented model, and in order to avoid emission double counting, raw material emissions are not aggregated to product manufacturing, similarly transport and energy consumption are considered separately.

To conclude, Matthews et al. [20] highlight the importance of a footprint estimation that includes the total SC up to the production gate, also known as cradle-to-grave approach (tier 3). Furthermore, the authors refer to tier 4 emission estimations when the whole product life cycle is taken into account by considering emissions occurring during distribution and product end of life. This extended scope is expected to better aid effective environmental strategies since both firms and consumers have an important influence over the footprints through their ‘purchase’ decisions.

3 The Mathematical Formulation

This chapter describes, besides the methodology, also a tool that can be used to assist in the planning and design of a biomass SC under economical and environmental impact considerations. The resulting model is solved by using a multi-objective MILP (moMILP) algorithm, which allows observing possible environmental trade-offs between damage categories and the economic indicator.

The mathematical formulation of the LCA-SC problem is briefly described next. The variables and constraints of the model can be roughly classified into three groups. The first one concerns process operations constraints given by the SC topology. The second one deals with the environmental model used while the third refers to the economic metric applied.

3.1 Supply Chain Design: Planning Model

The design-planning approach presented is a translation of the state task network (STN) formulation [21] to SC modelling, which is adapted from the work of Laínez et al. [22]. Such a formulation is suitable to collect all SC node information through a single variable, which eases the environmental and economic metrics formulation. This way SC node characteristics are modelled with a single equation set, since manufacturing nodes and distribution centres are treated in the same way as production and distribution activities. Subsequently, it turns out that the most important model variable is $P_{ijff't}$; which represents the specific activity of task i performed using technology j receiving input materials from site f and 'delivering' output materials to site f' during period t. Indeed, to model a production activity it must receive and deliver material within the same site (P_{ijff}). In case of a distribution activity, facilities f and f' must be different. The model's equations are briefly described in the next paragraphs. The separation between tasks and technologies allows for a flexible formulation of different scenarios.

Materials mass balance must be satisfied at each one of the nodes. The expression for the mass balance for each material (state in the STN formulation) s consumed at each potential facility f in every time period t is presented next. Parameter α_{sij} is defined as the mass fraction of material s that is produced by task i performed using technology j; T_s set refers to those tasks that have material s as output, while $\bar{\alpha}_{sij}$ and $\bar{T}_s$ set, refer to tasks that consume material s (Eq. 1).

$$S_{sft} - S_{sft-1} = \sum_{f'} \sum_{i \in T_s} \sum_{j \in \left(J_i \cap \tilde{J}_{f'}\right)} \alpha_{sij} P_{ijf'ft} - \sum_{f'} \sum_{i \in \bar{T}_s} \sum_{j \in \left(J_i \cap \tilde{J}_f\right)} \bar{\alpha}_{sij} P_{ijff't} \quad \forall s, f, t \qquad (1)$$

The model assumes that process parameters are fixed (such as reaction conversion, separation factors and temperatures). This assumption is acceptable for most activities. Notice that the recipe for a given activity is fixed and given by the parameters α_{sij} and $\bar{\alpha}_{sij}$; however, there are activities for which it may be desirable to let the model specify the mixture of inputs in order to achieve a given value for a specific biomass property (i.e., moisture content). For such activities the proportion of the different possible feedstocks should be variable. In order to account for those activities the mass balance shall be modified as shown in Eq. 2.

$$\begin{aligned} S_{sft} - S_{sft-1} = & \sum_{f'} \sum_{i \in T_s} \sum_{j \in \left(J_i \cap \tilde{J}_{f'}\right)} \alpha_{sij} P_{ijf'ft} - \sum_{f'} \sum_{i \in \bar{T}_s} \sum_{j \in \left(J_i \cap \tilde{J}_f\right)} \bar{\alpha}_{sij} P_{ijff't} \\ & + \sum_{i \in T_s} \sum_{j \in \left(J_i \cap \tilde{J}_{f'}\right)} Pv_{sijft} - \sum_{i \in \overline{T}_s} \sum_{j \in \left(J_i \cap \tilde{J}_f\right)} Pv_{sijf't} \quad \forall s, f, t \end{aligned} \tag{2}$$

For these flexible activities, it is necessary to make sure that the energy balance is achieved. This is done by introducing Eq. 3. Here, HV_{si} is the heating value for material s in activity i. Notice that heating values for feedstock are fixed. An activity changes the output heating value if (i) it is a pre-treatment task that modifies the biomass properties; or if (ii) it is a task that just changes the shape/appearance of biomass but it is receiving different kinds of biomass as input.

$$\sum_{s \in S_i} HV_{si} Pv_{sijft} = \sum_{s \in \overline{S}_i} HV_{si} Pv_{sijf't} \quad \forall i \in \bar{I}, j, f, t \tag{3}$$

Let us consider that a flexible activity must accomplish a total moisture content. In such a case, constraint (4) must be satisfied. Parameters Water_s and $\mathrm{Water}_{ij}^{\max}$ express the moisture content for material s and the maximum moisture content permitted for task i performed in equipment j.

$$\sum_{s \in S_i} \mathrm{Water}_s Pv_{sijft} \le \mathrm{Water}_{ij}^{\max} \sum_{s \in \overline{S}_i} Pv_{sijf't} \quad \forall i \in \bar{I}, j, f, t \tag{4}$$

Equation 5 models the temporal changes in facility capacities, in this sense the model allows for the simultaneous consideration of design and retrofit of SCs. Equation 6 serves for total capacity $\left(F_{jft}\right)$ bookkeeping taking into account the amount increased during planning period $t\left(\mathrm{FE}_{jft}\right)$.

$$V_{jft} \mathrm{FE}_{jft}^{L} \le \mathrm{FE}_{jft} \le V_{jft} \mathrm{FE}_{jft}^{U} \qquad \forall f, j \in \tilde{J}_f, t \tag{5}$$

$$F_{jft} = F_{jft-1} + \mathrm{FE}_{jft} \qquad \forall f, j \in \tilde{J}_f, t \tag{6}$$

Equation 7 ensures the total production rate in each plant to be greater than a minimum desired production rate and lower than the available capacity. Furthermore, parameter β_{jf} defines a minimum utilisation rate of technology j in site f, while $\theta_{ijff'}$ determines the resource utilisation factor.

$$\beta_{jf} F_{jft-1} \le \sum_{f'} \sum_{i \in I_j} \theta_{ijff'} P_{ijff't} \le F_{jft-1} \qquad \forall f, j \in \tilde{J}_f, t \tag{7}$$

$\theta_{ijff'}$ is the capacity utilisation rate of technology j by task i whose origin is location f and destination location f'. This parameter is one of the key factors to be determined when addressing aggregated planning problems, considering strategic and tactical decisions. This operational model may be applied in continuous as well as in semi-continuous processes. First, let us consider the continuous processes. For these cases, the capacity utilisation factor is a conversion factor, which allows taking into account the equipment j capacity in site f in terms of task i kg of produced material per time unit. In this way, the θ_{ijff} factor is the maximum throughput per planning period. On the other hand, this parameter is closely related to tasks operation time in the case of semi-continuous (batch) processes. Note that in this kind of production processes, the time period scale utilised in aggregated planning is usually larger than the time a task (production/distribution activity) requires to be performed. Therefore, the sequencing-timing problem of short-term scheduling is transformed into a rough capacity problem where aggregated figures are used. It is important to have in mind that capacity is expressed as equipment j available time during one planning period, then $\theta_{ijff'}$ represents the time required to perform task i in equipment j per unit of produced material. Thus, once operation times are determined this parameter can be easily estimated. Equation 8 forces the amount of raw material s purchased from site f at each time period t to be lower than an upper bound given by physical limitations $\left(A_{sft}\right)$. Also, the model assumes that part of the demand can actually be left unsatisfied because of limited production or supplier capacity. Thus, Eq. 9 forces the sales of product s carried out in market f during time period t to be less than or equal to demand.

$$\sum_{f'}\sum_{i\in \bar{T}_s}\sum_{j\in J_i} P_{ijff't} \le A_{sft} \qquad \forall s \in \mathrm{RM}, f \in \mathrm{Sup}, t \tag{8}$$

$$\sum_{f'}\sum_{i\in T_s}\sum_{j\in J_i} P_{ijf'ft} \le \mathrm{Dem}_{sft} \qquad \forall s \in \mathrm{FP}, f \in \mathrm{Mkt}, t \tag{9}$$

For further model details the reader should refer to Laínez et al. [22].

3.2 Supply Chain: Environmental Model

The application of the LCA methodology to a SC requires four steps, namely (i) goal setting, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment (LCIA) and (iv) results interpretation towards improvement.

Regarding goal setting, it is important to define the boundaries of the system under study, and which is the functional unit (FU) that the SC will provide. Boundaries in the case of the chemical industry in general and in the case of Biomass SCs are usually drawn from cradle-to-grave, this is due to the fact that most of these SC products (chemicals and electricity) are used in different ways and the use phase of products made from these products is too difficult to model appropriately. Consequently raw material extraction, its processing and shipment to a market are considered as part of the SC system. Regarding the FU, commonly a certain amount of product produced is considered. In this sense it is advisable to compare different SCs in terms of the fulfilled amount of sales or portion of demand satisfied [12].

The LCI step requires the estimation of SC environmental interventions (emissions or natural raw material consumptions) which requires assessment of raw material producers, transportation and product processing impacts. This step is the most time consuming within a LCA due to the large amount of information that is required to be gathered, however the usage of LCI databases eases this issue. More importantly the use of a mathematical model helps in calculating the appropriate LCI for the optimal SC configuration.

The results of the LCI step of the LCA can be interpreted by means of different environmental metrics. Environmental interventions are translated into metrics related to environmental impact as end-points or mid-points metrics by the usage of characterisation factors (CFs). This translation is the Life Cycle Impact Assessment (LCIA) step. The metrics used differ in their position along the environmental damage chain (environmental mechanism).

The equations of the environmental model are briefly described next. Equation 10 models IC_{aft} which represents the mid-point a environmental impact associated to site f which rises from activities in period t; $\psi_{ijff'a}$ is the a environmental category impact CF for task i performed using technology j, receiving materials from node f and delivering them at node f'.

$$\mathrm{IC}_{aft} = \sum_{j \in \tilde{J}_f} \sum_{i \in I_j} \sum_{f'} \psi_{ijff'a} P_{ijff't} \qquad \forall a, f, t \tag{10}$$

Similarly to the case of α_{sij} and $\bar{\alpha}_{sij}$, the value of $\psi_{ijff'a}$ is fixed and constant, provided that all environmental impacts are directly proportional to the activity performed in that node $\left(P_{ijfft}\right)$. This issue is a common practice in LCA, where all direct environmental impacts are considered linear with respect to the FU [23]. In the case of transportation the FU commonly considered is the amount of material (kg) transported a given distance (kg km). Consequently the value of $\psi_{ijff'a}$ can be calculated by Eq. 11 in the case of transportation, which considers the distance between sites $\left(\mathrm{distance}_{ff'}\right)$ and where ψ^{T}_{ija} represents the a environmental category impact CF for the transportation of a mass unit of material over a length unit. The study of environmental impacts associated to transport or production can be performed by setting the indices summation over the corresponding tasks (i.e., $i \in Tr$ or $i \in NTr$). It should be noted that environmental impacts associated to materials transport are assigned to their origin node.

$$\psi_{ijff'a} = \psi^{T}_{ija} \mathrm{distance}_{ff'} \qquad \forall i \in Tr, j \in J_i, a, f, f' \tag{11}$$

Equation 12 introduces DamC_{gft} which are a weighted sum of all mid-point environmental interventions combined using g end-point damage factors ζ_{ag} and then further normalised with NormF_g factors. Equation 13 is used to compute the g normalised end-point damage along the whole SC $\left(\mathrm{DamC}_g^{\mathrm{SC}}\right)$.

$$\mathrm{DamC}_{gft} = \sum_{a \in A_g} \mathrm{NormF}_g \zeta_{ag} \mathrm{IC}_{aft} \qquad \forall g, f, t \tag{12}$$

$$\mathrm{DamC}_g^{\mathrm{SC}} = \sum_f \sum_t \mathrm{DamC}_{gft} \qquad \forall g \tag{13}$$

Equations 14 and 15 sum up the environmental damage category results for each site f and for the whole SC, respectively.

$$\mathrm{Impact}_f^{2002} = \sum_g \sum_t \mathrm{DamC}_{gft} \qquad \forall f \tag{14}$$

$$\mathrm{Impact}_{\mathrm{overall}}^{2002} = \sum_f \sum_g \sum_t \mathrm{DamC}_{gft} \qquad \forall f \tag{15}$$

$\mathrm{DamC}_g^{\mathrm{SC}}$ or $\mathrm{Impact}_{\mathrm{overall}}^{2002}$ are both used as objective functions in the moMILP formulation. In this sense the use of damage categories is sometimes preferred given that they are easier to comprehend compared to mid-point values.

3.3 Economic Model

Many economic indicators have been proposed to assess the performance of a SC network design. The most traditional indicators are profit, NPV and total cost. Other more holistic measures have been recently proposed. Laínez et al. [24] proposed a model that pursues the maximisation of a financial key performance indicator, the corporate value of the firm at the end of the time horizon. The corporate value is computed by a discounted-free-cash-flow (DFCF) method which can be introduced as part of the mathematical formulation. Next, expressions to calculate (i) operating revenue, (ii) operating cost and (iii) capital investment are presented which would eventually permit integration with detailed financial models. Here, NPV will be used for the sake of simplicity and comprehensiveness. The application of other kind of metrics is out of the scope of this chapter, given the specific characteristics of the problem addressed in this work, but they are discussed under chapter Global Clean Gas Process Synthesis and Optimisation in Sect. 2.1

Operating revenue is calculated by means of net sales which are the income source related to the normal SC activities. Thus, the total revenue incurred in any period t can be easily computed from products sales executed in period t as stated in Eq. 16.

$$\mathrm{ESales}_t = \sum_{s \in \mathrm{FP}} \sum_{f \in \mathrm{Mkt}} \sum_{f' \notin (\mathrm{Mkt} \cup \mathrm{Sup})} \mathrm{Sales}_{sf'ft} \mathrm{Price}_{sft} \qquad \forall t \tag{16}$$

In order to calculate overall operating cost an estimation of fixed costs and variable costs is required. The total fixed cost of operating a given SC structure can be computed using Eq. 17. Where FCFJ_{jft} is the fixed unitary capacity cost of using technology j at site f.

$$\mathrm{FCost}_t = \sum_{f \notin (\mathrm{Mkt} \cup \mathrm{Sup})} \sum_{j \in \tilde{J}_f} \mathrm{FCFJ}_{jft} F_{jft} \qquad \forall t \tag{17}$$

The cost of purchases from supplier e, which is computed through Eq. 18, includes raw materials purchases, transport and production resources.

$$\mathrm{EPurch}_{et} = \mathrm{Purch}^{\mathrm{rm}}_{et} + \mathrm{Purch}^{\mathrm{tr}}_{et} + \mathrm{Purch}^{\mathrm{prod}}_{et} \qquad \forall e, t \tag{18}$$

The purchases $\left(\mathrm{Purch}^{\mathrm{rm}}_{et}\right)$ associated to raw materials made to supplier e can be computed through Eq. 19. Variable χ_{est} represents the cost associated to raw material s purchased from supplier e.

$$\mathrm{Purch}^{\mathrm{rm}}_{et} = \sum_{s \in \mathrm{RM}} \sum_{f \in F_e} \sum_{i \in \bar{T}_s} \sum_{j \in J_i} P_{ijfft} \chi_{est} \qquad \forall e \in E_{\mathrm{rm}}, t \tag{19}$$

The costs of transportation and production are determined by Eqs. 20 and 21, respectively. Here, $\rho^{tr}_{eff't}$ denotes the e provider unitary transportation cost associated to material movement from location f to location f' during period t. $\tau^{\mathrm{ut1}}_{ijfet}$ represents the unitary production cost associated to perform task i using technology j, whereas $\tau^{\mathrm{ut2}}_{sfet}$ represents the unitary inventory costs of material s storage at site f, both of them using provider e during period t.

$$\mathrm{Purch}^{\mathrm{tr}}_{et} = \sum_{i \in Tr} \sum_{j \in J_i \cap \bar{J}_e} \sum_{f} \sum_{f'} P_{ijff't} \rho^{\mathrm{tr}}_{eff't} \qquad \forall e \in \bar{E}_{tr}, t \tag{20}$$

$$\mathrm{Purch}^{\mathrm{prod}}_{et} = \sum_{f} \sum_{i \notin Tr} \sum_{j \in (J_i \cap \hat{J}_f)} P_{ijfft} \tau^{\mathrm{ut1}}_{ijfet} + \sum_{s} \sum_{f \notin (\mathrm{Sup} \cup \mathrm{Mkt})} S_{sft} \tau^{\mathrm{ut2}}_{sfet} \qquad \forall e \in \tilde{E}_{\mathrm{prod}}, t \tag{21}$$

In the case of $\tau^{\mathrm{ut1}}_{ijfet}$, this parameter entails restrictions associated with α_{sij} and $\bar{\alpha}_{sij}$, which forces the plant to operate at the same fixed conditions, meaning that the amount of utilities and labour spent is proportional to the amount of raw material processed. However the utilities and labour unitary cost may change over time. Moreover, possible cost decrease associated to economies of scale are disregarded by using the former assumption, higher production rates are associated linearly to higher production costs. Finally, the total investment on fixed assets is computed through Eq. 22. This equation includes the investment made to expand the technology's capacity j in facility site f in period t $\left(\mathrm{Price}^{\mathrm{FJ}}_{jft} \mathrm{FE}_{jft}\right)$.

$$\mathrm{FAsset}_t = \sum_f \sum_j \mathrm{Price}^J_{jft}\mathrm{FE}_{jft} + I^J_{ft}\mathrm{JB}_{ft} \qquad \forall t \tag{22}$$

Equation 23 represents the calculation of profit at period t. To conclude, NPV is computed by means of Eq. 24.

$$\mathrm{Profit}_t = \mathrm{ESales}_t - \left(\mathrm{FCost}_t + \sum_e \mathrm{EPurch}_{et}\right) \quad \forall t \tag{23}$$

$$\mathrm{NPV} = \sum_t \left(\frac{\mathrm{Profit}_t - \mathrm{FAsset}_t}{(1+\mathrm{rate})^t}\right) \tag{24}$$

The selection of the discount rate (*rate*) for any time discounted metric is subject to controversy, given that it represents the trade-off between the enjoyment of present and future benefits and affects directly intergenerational aspects of sustainability. Higher values of *rate* devaluate future impacts and consequently they count little on long time horizon projects, which could be perceived as contrary to the interest of future generations. Identically to the case of a weighting set for a composite environmental index, the selection of a given discount rate is highly subjective and should represent the decision makers belief in terms of intergenerational aspects.

Finally, the SC network design-planning problem whose objective is to optimise a given set of objective functions can be mathematically posed as follows:

$$\underset{\mathcal{X},\mathcal{Y}}{\mathrm{Min}} \left\{ -\mathrm{NPV}, \mathrm{DamC}^{\mathrm{SC}}_g, \mathrm{Impact}^{2002}_{\mathrm{overall}} \right\}$$

subject to Eqs. 2 – 24

$$\mathcal{X} \in \{0,1\}; \mathcal{Y} \in \mathbb{R}^+$$

Here X denotes the binary variables set, while Y corresponds to the continuous variable set.

4 Case Study: A Biomass Supply Chain Geographically Located in Spain

The case study used to illustrate the concepts behind the presented design strategy addresses a Biomass SC problem comparing the generation of electricity and H_2 from two different kinds of feedstock: (i) different biomass wastes and (ii) coal, which is a wide extended fossil fuel resource. The SC under study comprises biomass collection sites and processing sites where biomass is pre-treated and used, in distribution centres and marketplaces.

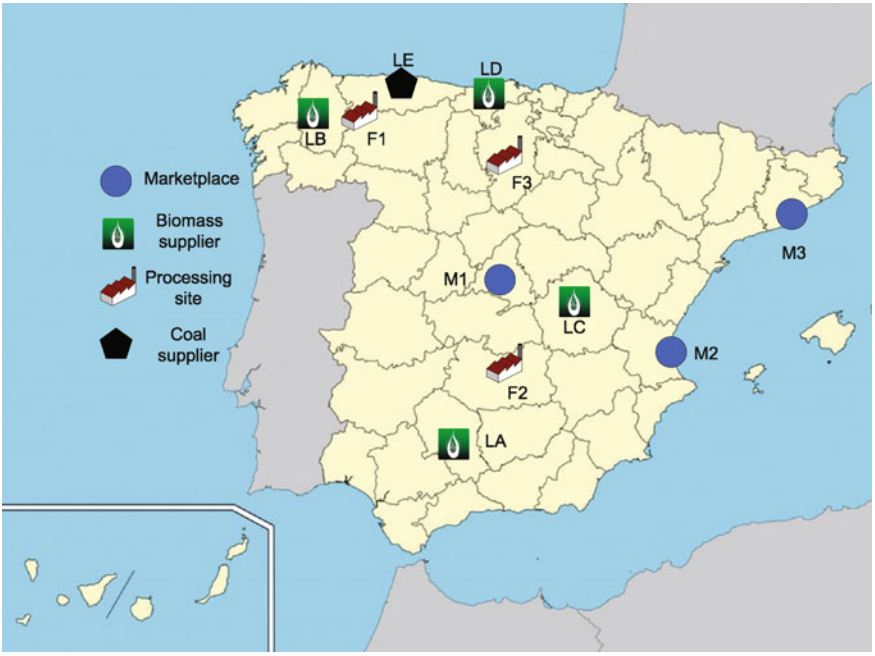


Fig. 3 Location map for the potential SC network

A simplified potential network is proposed and restricted to Spain (see Fig. 3). Lugo (*F*1), Ciudad Real (*F*2) and Burgos (*F*3) are considered to be possible facilities location nodes. The feedstock is supposed to be available at Cordoba (*LA*), Lugo (*LB*), Cuenca (*LC*), Santander (*LD*) and Oviedo (*LE*). This last site is the one supplying coal. Hydrogen is supposed to be sold at three market places located at Madrid (*M*1), Valencia (*M*2) and Barcelona (*M*3), while electricity is fed to the Spanish electricity network at their respective generation places.

Different biomasses are modelled considering that each of them possesses different energy content and moisture. Table 1 shows the characteristics of the considered feedstocks, biomass wastes with useable energy content (see chapter Raw Materials, Selection, Preparation and Characterization) that can be found in Spain. Biomass types, approximate availability, costs and moisture contents are based on data published in Gomez et al. [25], Van Dyken et al. [10], Rentizelas et al. [8] and Panichelli and Gnansounou [4]. Lower heating values (LHV) for biomasses are taken from Phyllis database [26]. Hypothetically, coal has been considered as a dry material which does not require any pre-treatment. It is interesting to observe that higher moisture contents are present in forest and wood residues. Olive residues have low moisture content and high heating value which is comparable to the one of the sub-bituminous coal considered here.

The biomass may be *pre-treated* before being finally processed. Figure 4 depicts the different pre-treatment processes that may be applied to the biomass

Table 1 Feedstock properties. LHV is in ar (as received) basis; Wt: Weight

Biomass	Cost (€ ton^{-1})	Lower Heating Value, (MJ/kg)	Moisture content (%wt)	Seasonality	Monthly availability (tons)	Source location
Forest wood residue	25	8.597	48.9	None	40,500	LA
Pine waste	35	10.450	40	None	3,350	LB
Almond tree prunings	40	11.313	40	December to February	12,400	LC
Olive pomace	65	19.098	7.6	January to March	73,400	LD
Olive pit	35	18.778	6.1	February to May	27,900	LD
Coal	45	15.000	–	None	65,000	LE

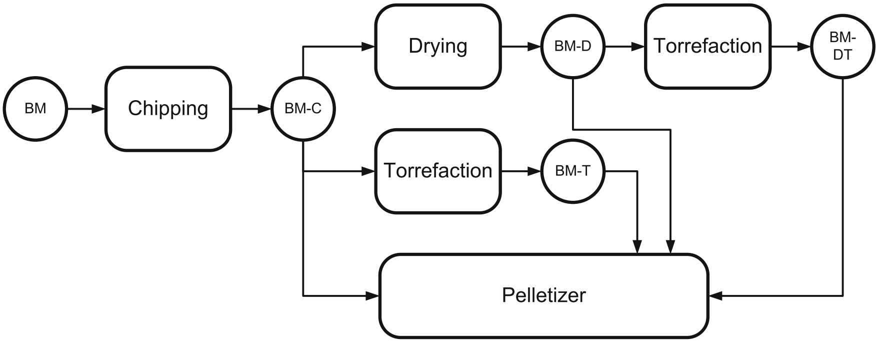


Fig. 4 STN representing the pre-treatment activities for a generic biomass

(BM) so that it achieves the adequate shape and properties (energy content and humidity) to follow up later processes. Several conditions have been assumed to select the specific path of pre-treatment units for each feedstock. They depend basically on the moisture content, shape and LHV of the input required for the treatment plant. Energy densification and matter densification through drying as well as dry matter loss in the different processes affecting the heating value have been considered. Nevertheless, in this case study BM bulk density has not been considered for the sake of simplicity and also given the planning horizon required for the strategic decisions that are being addressed. Note that coal does not need any pre-treatment. The characteristics for the pre-treatment processes are presented in Table 2 The data are from Panichelli and Gnansounou [4] and from Hamelinck et al. [5]. The pre-treatment options considered here are:

- *Chipper*: Transformation of the biomass as received, into chips. It is the first biomass size reduction step, and mandatory for all the biomass sources considered. It is considered that a first step of shape homogenisation is crucial for an integrated Biomass SC. Moisture content is not modified, but there exists a loss of dry matter, which is considered.

Table 2 Pre-treatment processes and their main modelling assumptions

Activity/ equipment	Moisture losses (%)	Dry matter losses (%)	Operating cost (€ ton^{-1})	Capacity (tons h^{-1})	Investment (1×10^6 €)	Electricity consumption (MWh ton^{-1})
Chipper	0	0.17	2.5	30	0.370	5
Dryer	88	0.08	55	100	5.000	20
Torrefactor	55	19	40	20	0.100	37
Pelletizer	0	0	3.5	6	0.485	30

Table 3 Parameters for the processes for electricity and H_2 generation

Technology	Operating cost (€)	Capacity	Investment (1×10^6 €)	Product price (€)	Total monthly demand
Electricity	34.2 MWh^{-1}	300 MW	860	0.151 kWh^{-1}	75,000 MWh
H_2	1,880 ton^{-1}	33.6 tons h^{-1}	1,500	3 kg^{-1}	650 ton

- *Dryer*: Active dryer is needed when the source has too high moisture contents. The condition to enter this step is to have a humidity higher than 7%. Passive drying is assumed not to be significant according to the unit of time that the model considers. The dry matter loss is insignificant if compared with the moisture loss.
- *Torrefactor*: Its main objective is the LHV increase through volatiles release in an inert atmosphere. The biggest dry matter loss is obtained here, and the drying process also takes place. The condition to pass through this unit is to have a LHV lesser than 15 MJ/kg.
- *Pelletizer*: In this case study we assume that the biomass must be pelletized before its final transformation, thus a high homogeneous raw material is arriving to the final plants. Note that the pelletizer requires input to have humidity equal to or lower than 7%. This requirement may be fulfilled by mixing different types of biomasses or pre-treated material. It is the main characteristic of this unit (note that no moisture or dry matter losses are considered here).

The technology that is employed to provide the final product is gasification. An integrated gasification combined cycle (IGCC) power plant is assumed for the electricity generation, and a gasification plant with carbon capture and storage (CCS) for the H_2 generation. Efficiencies of 40 and 30% are assumed for each plant, respectively, the adoption of such figures will be extensively discussed in chapter Modelling Superstructure for Conceptual Design of Syngas Generation and Treatment. It is assumed that the lower capacity that can be installed for the energy generator is 85 MWh. Other relevant information concerning these technologies is presented in Table 3. These data are from Pérez-Fortes et al. [27] and IEA-GHG [28]. Biomass and H_2 transportation prices were estimated at 0.03 and 0.05 € ton^{-1} km^{-1} from current economical trends, respectively. The demand of H_2 is evenly distributed along the three markets (*M*1, *M*2 and *M*3, while the demand of electricity is supplied to the grid from any facility location). It is assumed that the demand must be completely satisfied. For the case of NPV optimisation return rate is assumed to be 8% which is a common value for this kind of projects.

In order to assess the environmental impact associated to the biomass-based energy SC, the available LCI values were retrieved from the LCI database EcoinventV1.3 [29] and using SimaPro 7.1.6 [30] and converted directly to the IMPACT 2002+ mid-point indicators. For those activities which were not available, the impacts were assumed based on similar products or activities. The environmental impacts associated to energy generation, H_2 production and pre-treatment processes without consideration of feedstock and transportation consumption are found in Table 4. The environmental impact for transportation activities is presented in that table as well. The environmental impact for feedstock can be found in Table 5 which does not consider impacts associated to transportation.

The project is evaluated along a planning horizon of 25 years, considering monthly planning decisions. The model has been implemented in GAMS which is an algebraic modelling software. The formulation of the SC-LCA model leads to a MILP with 4,159 equations, 41,221 continuous variables and 96 discrete variables. It takes 61 CPU seconds to reach a solution with a 0.1% integrality gap on a 2.0 GHz Intel Core 2 Duo computer using the MIP solver of CPLEX.

Figure 5 shows the obtained dominant biomass-based SC that maximises NPV. It is found that the three potential locations are considered and on each one of them a facility is opened. All pre-treatment technologies are installed in location *F*1 besides the required equipment to produce H_2. From this site H_2 is delivered to all markets. Note that *F1* is collecting all the forest wood residues (FWR) for which larger mass flows are required due to their low LHV. By establishing *F1*, which is near to the FWR collection site, significant savings in transportation are obtained. The electricity is generated in site *F2*. In this site; equipments to perform chipping, drying and pelletising are installed. The electricity demand of each market is satisfied from site *F2*. Site *F3* is used just as a distribution centre for pre-treated biomass. Equipment for chipping and drying is installed in such a site.

Table 6 shows the proposed capacity to be installed for each of the equipments at every site to obtain the maximum NPV configuration. Notice that for this configuration there are some inter-site flows, clearly showing the capabilities of the model to tackle with inter-site distribution tasks. Forest wood residues which have been dried and torrefied are being sent from site *F1* to *F2*, while *F3* is transferring dried pine waste and dried almond tree pruning to location *F2* in order to be converted to energy later on. By having material flows of pre-treated biomass the transportation cost is reduced due to the mass decrease that is achieved through the utilisation of such processes.

The optimal configuration for the environmental impact has also been obtained. Figure 6 shows the minimum IMPACT 2002+ configuration for the biomass-based SC. Please note that this supply chain fulfills with the same demand as the one obtained by optimising NPV. The capacity proposed to be installed for the equipment of this configuration is presented in Table 7. Note that for this case the location *F3* is not considered, and all biomass is sent from the collection sites to locations *F1* and *F2*. This configuration is satisfying the demand of electricity from both locations *F1* and *F2*, whereas H_2 is delivered from site *F2*. There is one

Table 4 Environmental impacts associated to SC tasks

Mid-point categories	Chipper (points ton^{-1})	Dryer (points ton^{-1})	Torrefactor (points ton^{-1})	Pelletizer (points ton^{-1})	Electricity generator (points GJ^{-1})	H_2 generator (points ton^{-1})	Transport. (points ton^{-1} km^{-1})
Carcinogens	2.16E−06	8.64E−06	1.60E−05	1.30E−05	0.00E+00	0.00E+00	6.93E−08
Non-carcinogens	9.28E−06	3.71E−05	6.86E−05	5.57E−05	0.00E+00	0.00E+00	4.93E−07
Respiratory inorganics	4.18E−04	1.67E−03	3.10E−03	2.51E−03	2.09E−03	2.49E−01	2.38E−05
Ionizing radiation	6.03E−06	2.41E−05	4.46E−05	3.62E−05	0.00E+00	0.00E+00	5.17E−09
Ozone layer depletion	1.23E−08	4.93E−08	9.11E−08	7.39E−08	0.00E+00	0.00E+00	2.58E−09
Respiratory organics	6.01E−08	2.40E−07	4.45E−07	3.61E−07	0.00E+00	0.00E+00	3.43E−08
Aquatic ecotoxicity	3.40E−07	1.36E−06	2.51E−06	2.04E−06	0.00E+00	0.00E+00	2.23E−08
Terrestrial ecotoxicity	6.50E−06	2.60E−05	4.81E−05	3.90E−05	0.00E+00	0.00E+00	5.34E−06
Terrestrial acid/nutri	5.75E−06	2.30E−05	4.26E−05	3.45E−05	6.91E−05	8.23E−03	5.13E−07
Land occupation	1.30E−07	5.20E−07	9.63E−07	7.80E−07	0.00E+00	0.00E+00	1.61E−10
Aquatic acidification	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Aquatic eutrophication	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Global warming	2.57E−04	1.03E−03	1.90E−03	1.54E−03	2.06E−02	2.45E+00	1.37E−05
Non-renewable energy	3.22E−04	1.29E−03	2.39E−03	1.93E−03	0.00E+00	0.00E+00	1.34E−05
Mineral extraction	2.96E−09	1.19E−08	2.19E−08	1.78E−08	0.00E+00	0.00E+00	4.54E−12

Table 5 Environmental impacts associated to feedstock production (points ton^{-1})

Mid-point categories	Forest wood residue	Pine waste	Almond tree prunings	Olive pomace	Olive pit	Coal
Carcinogens	2.12E−05	2.18E−05	1.96E−05	2.84E−05	9.40E−06	1.51E−04
Non-carcinogens	1.37E−05	1.31E−05	1.53E−05	3.28E−05	1.76E−06	2.52E−04
Respiratory inorganics	1.16E−03	1.19E−03	1.08E−03	1.11E−03	4.36E−04	2.89E−02
Ionizing radiation	2.62E−05	2.42E−05	3.12E−05	4.77E−06	2.64E−07	9.37E−05
Ozone layer depletion	1.05E−07	1.07E−07	1.00E−07	8.00E−08	3.70E−08	1.42E−06
Respiratory organics	5.52E−06	6.22E−06	3.71E−06	2.25E−06	4.95E−06	2.28E−05
Aquatic ecotoxicity	1.24E−06	1.15E−06	1.44E−06	1.89E−06	6.60E−08	2.13E−04
Terrestrial ecotoxicity	5.05E−05	4.91E−05	5.42E−05	1.10E−04	6.64E−06	8.41E−03
Terrestrial acid/nutri	1.89E−05	1.97E−05	1.67E−05	1.68E−05	8.28E−06	6.78E−04
Land occupation	1.90E−03	1.62E−03	2.62E−03	4.80E−03	1.38E−03	1.63E−04
Aquatic acidification	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Aquatic eutrophication	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Global warming	1.08E−03	1.05E−03	1.16E−03	4.50E−04	1.88E−04	1.57E−02
Non-renewable energy	1.49E−03	1.43E−03	1.65E−03	5.72E−04	1.97E−04	1.84E−01
Mineral extraction	6.52E−08	6.69E−08	6.05E−08	6.75E−07	3.59E−08	7.72E−07

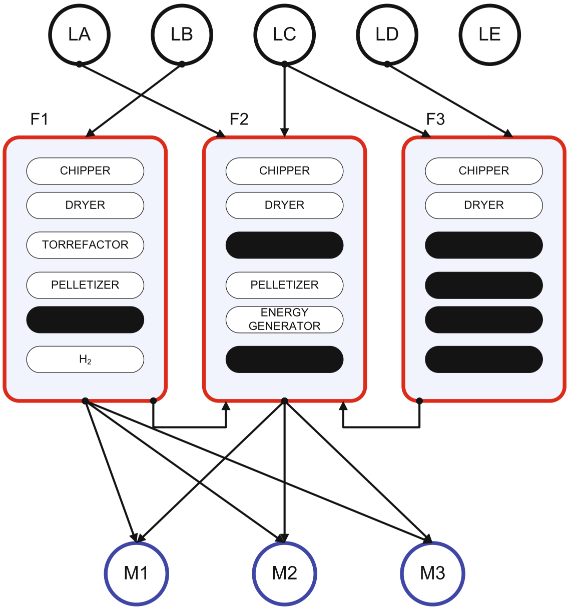


Fig. 5 Optimum NPV network configuration for the biomass-based SC

Table 6 Equipment capacity for the optimum NPV Biomass SC

Equipment	Facility		
	F1	F2	F3
Chipper (tons h^{-1})	67.5	60.4	40.0
Dryer (tons h^{-1})	47.4	20.7	20.0
Torrefactor (tons h^{-1})	55.8	–	–
Pelletizer (tons h^{-1})	23.2	60.3	–
Electricity (GJ h^{-1})	–	450.0	–
H_2 (tons h^{-1})	1.1	–	–

inter-site flow from site *F2* to *F1*, which corresponds to a flow of dried olive pomace, in this environmental friendly configuration.

Recall that we introduced a 'flexible' task to account for those tasks for which we would like the model to decide how to better mix different biomasses so as to achieve a given specified biomass property. We have assumed that the pelletizer is one of such tasks for this case study. To give an example, there are periods in which the model proposes to make the following mix: 1.4% forest wood residues, 30.3% dried and torrefied forest wood residues, 10.5% dried pine waste, 14.4% dried almond tree prunings and 43.5% chipped olive pomace (mass basis). This mixture is then fed to the syngas production plant. The values of humidity corresponding to these materials are 10.0, 6.0, 7.0, 7.0 and 7.5%, respectively. It can be proved that the humidity of this mix is 7.0% which is the maximum humidity allowed for the pelletizer input.

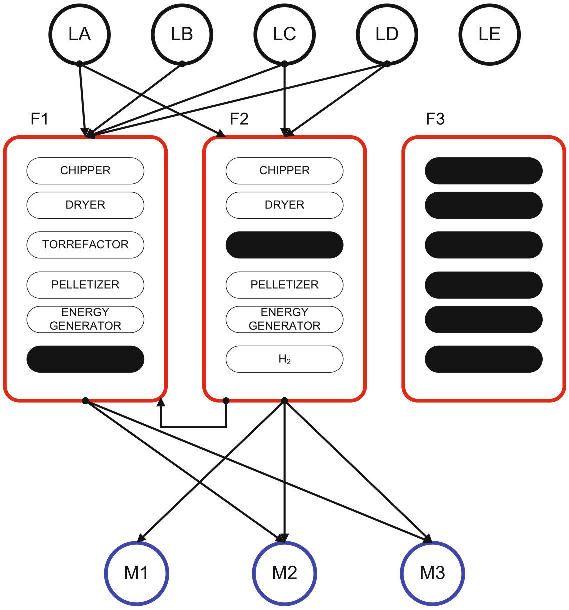


Fig. 6 Optimum Impact 2002+ network configuration for the biomass-based SC

Table 7 Equipment capacity for the optimum Impact 2002+ Biomass SC

Equipment	Facility		
	F1	F2	F3
Chipper (tons h^{-1})	73.1	70.3	–
Dryer (tons h^{-1})	54.4	20.7	–
Torrefactor (tons h^{-1})	51.7	–	–
Pelletizer (tons h^{-1})	40.0	62.7	–
Electricity (GJ h^{-1})	300.0	300.0	–
H_2 (tons h^{-1})	–	1.1	–

Tables 8 and 9 summarize the most significant values corresponding to both solutions regarding environmental and economic aspects. By deploying the SC configuration corresponding to the more profitable SC configuration, a NPV equal to 228.51 M€ is obtained. This value is reduced by 3% when the environmental friendly configuration is established. Note that the main difference between these two configurations is the investment required for installing the proposed capacity in the different sites. For the case of NPV maximisation the installation of an electricity generation plant at location *F2* makes it necessary to send larger amount of biomass to this site. In order to reduce this additional cost a distribution centre at location *F3* is established where biomass is treated before being transferred to the other sites. The reduction in capacity investment offsets, the increase in the transportation cost and the extra costs are associated to the pre-treatment of biomass. Table 8 also shows the payback periods and internal rate of return for both solutions.

Table 8 Economic aspects arising from single objective optimisation (NPV and Impact 2002+) (M€)

	Impact 2002+ optimisation	NPV optimisation
Investment	170.21	148.13
Biomass cost	820.16	819.87
Transportation cost	92.73	122.65
Production cost	2,222.77	2,224.02
Sales	3,987.00	3,987.00
Profit	851.34	820.46
NPV[a]	220.59	228.51
IRR (%)[b]	24.02	27.38
Payback period (years)	5.00	4.51

[a] Based on a return rate of 8%

[b] Based on a planning horizon of 25 years

Table 9 Environmental impacts arising from single economic and overall environmental objective function optimisation results (Impact 2002+ points per year)

End-point impact category	Impact 2002+ optimisation	NPV optimisation
Human health	16,255.29	17,267.21
Ecosystem quality	3,375.79	3,610.96
Climate change	90,383.37	90,950.66
Resources	5,292.64	5,852.73
Impact 2002+	115,307.09	117,681.56

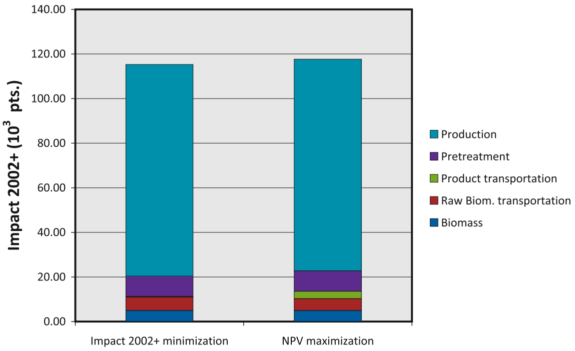


Fig. 7 Distribution of annual environmental impacts for single objective optimisation solutions, according to different SC activities

With regard to environmental interventions, the NPV optimum solution renders an environmental impact of 117681 pts. The environmental friendly configuration can slightly reduce the impact by 2%. Notice that the impacts for each damage category (see Table 9) are very similar for both solutions. These configurations have a major impact on the climate change category which represents 78% of the overall impact. Figure 7 presents the distribution of environmental impacts according to different SC activities. Notice that as for the NPV comparison, the difference between the environmental impacts is mainly due to transportation.

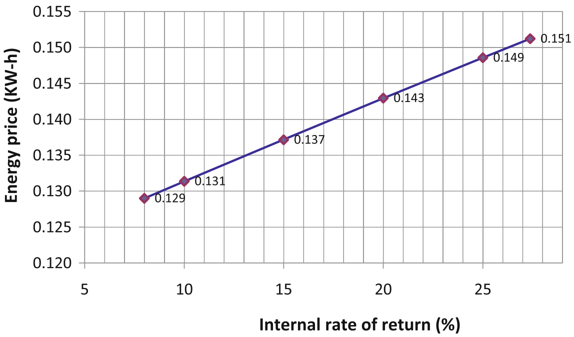


Fig. 8 Energy price versus internal rate of return for the biomass-based SC obtained by maximising NPV

In the presented case study electricity generation and H_2 production are the most important factors contributing to the overall environmental impact in both single objective optimisation cases; while biomass sourcing is the least impacting aspect. This clearly shows that activities to reduce environmental impact should be focused on improving the technologies used to produce energy and H_2.

We would like to highlight how sensitive the solutions for the biomass-based SC are to the final product prices. For instance if we assume that the energy price is reduced to 50% (i.e., 0.075 € kWh^{-1}) the NPV at the end of the planning horizon (i.e., 25 years) would be negative and equal to -553.25×10^6 €. The price that renders an internal rate of return of 8% considering a project life time of 25 years is 0.129 € kWh^{-1}. Any price below this value would require some sort of subsidy. Figure 8 shows the energy prices that are required for different internal rates of return.

For comparison purposes the optimal SC based on coal has been also obtained. The optimal NPV configuration for this case proposes to deliver electricity from location *F1*, where a capacity of 450 GJ h^{-1} is installed, while the H_2 is produced at location *F3* where a capacity of 1.1 tons h^{-1} is installed. The minimum Impact 2002+ solution for this case (where coal is the only raw material available) is the same as the one obtained by the NPV optimisation. The reason is that the only way to improve the environmental impacts is by means of transportation, which is the case of NPV optimisation since there are no pre-treatment associated with coal. This solution is summarised in Tables 10 and 11. Note that an NPV improvement of 219% can be gained by utilising coal as feedstock when compared to the biomass-based SC. Notice that the main difference is from the production cost which is due to the pre-treatment activities that are required in the biomass-based SC. This fact also makes the investment increase in the Biomass SC.

Regarding the environmental impacts, the Impact 2002+ is increased in 203% compared with the biomass-based SC. It is noteworthy that the impact associated with the climate change category is very similar for both cases. We have to bear in mind that CO_2 is still emitted when using a Biomass SC, however this biomass is regenerated faster than fossil fuels. Nevertheless, the other categories are significantly increased specially for the case of resources and human health. The resource regeneration issue is the reason why the impact related to the resources category is

Table 10 Economic aspects arising from single objective optimisation for the coal-based SC (M€)

	NPV optimisation
Investment	111.74
Coal cost	839.55
Transportation cost	181.70
Production cost	1,136.10
Sales	3,987.00
Profit	1,829.65
NPV[a]	729.40
IRR (%)[b]	112.75
Payback period (years)	1.53

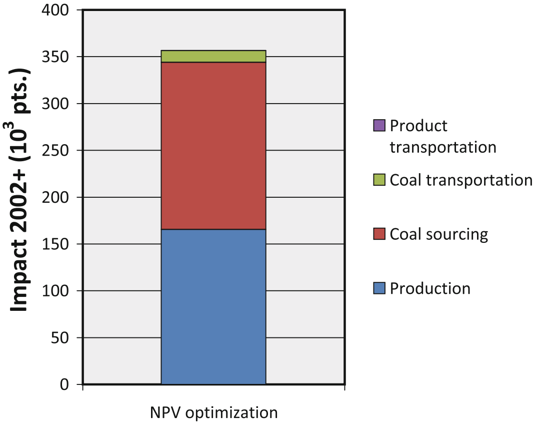
[a] Based on a return rate of 8%

[b] Based on a planning horizon of 25 years

Table 11 Environmental impacts arising from single economic and overall environmental objective function optimisation results for the coal-based SC (Impact 2002+ points per year)

End-point impact category	NPV optimisation
Human health	109,640.53
Ecosystem quality	11,077.16
Climate change	95,334.48
Resources	140,605.89
Impact 2002+	356,658.06

Fig. 9 Distribution of annual environmental impacts for the coal-based SC



larger in the coal-based case. This fact also emphasises the importance of having an overall impact indicator instead of a partial indicator such as CO_2 kg. Notice that if we compare the coal and biomass-based SCs based on CO_2 kg, there would not be an important reduction in the emissions to environmentally justify the project. Figure 9 shows the distribution of environmental impacts according to different SC activities for the coal-based SC. Notice that for the coal-based case the impact of production accounts for 46% of the overall impact. The other activity generating environmental impacts is the coal sourcing which accounts for the 50%

of the overall impact. Moreover, from Fig. 9, it can also be concluded that if the sourcing of raw materials would be disregarded then different solutions would be obtained. If we disregard the raw materials sourcing from the analysis, the biomass-based SC and the coal-based SC would result in a environmental impact of 112,701 and 178,225 points, respectively. This highlights the significance of a SC approach to the problem, rather than focusing only in the processing sites. This also points out the relevance of 'purchase' decisions on the environmental impact of an SC.

5 Conclusions

This chapter presents an approach for designing and planning efficient Biomass SCs. The model consists of a multi-period MILP that accounts for the multi-objective optimisation of economic and environmental interventions. The model considered the long-term strategic decisions (e.g., establishing of pre-treatment trains of units and their respective location, selection of biomass sources, location of processing sites and distribution centres). The problem has been formulated as a multi-objective optimisation, where two objective functions are considered, the net present value and the Impact 2002+ metric was adopted as a measure of overall environmental impact.

A biomass SC case study, geographically located in Spain, is presented here considering the availability of five different potential biomass waste sources. It has been considered that two final products, electricity and H_2, are delivered to marketplaces by means of gasification plants. The most environmental friendly and the most profitable SC configurations for this case study have been shown and their differences have been discussed. However, the indicator values were very similar. It was shown that the more impacting damage category was climate change which accounts for approximately 80% of the overall environmental impact. Moreover, the sensitiveness of the optimal solutions to change in prices and rate of return values was demonstrated. The most profitable SC results in a positive NPV, however reductions of product prices can easily lead to economic losses. The prices to achieve different internal rates over a project life time of 25 years were presented. For this specific case study it was demonstrated that if a return rate of 8%, which is typical for this type of projects, is required, the price cannot be lower than 0.129 € kWh^{-1}. Otherwise the project should be subject to a subsidy if it is meant to be sustainable. This demonstrates how this type of models can be used to determine subsidy policies in order to actually drive industry towards more environmental practices.

The problem was also solved for a coal-based SC. This comparison emphasised the relevance of (i) using an overall environmental impact rather than a partial metric such as kg of CO_2, and (ii) a supply chain approach to the problem so that the entire life cycle of the product and/or process is included and analysed. Narrower approaches (i.e., merely analyzing the processing/manufacturing sites) may lead to biased solutions when the magnitude of environmental impacts associated with producing, collecting or extracting the raw materials are considerably high.

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